EARLY DATA FROM AURA AND CONTINUITY FROM UARS AND TOMS

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Abstract. Aura, the last of the large EOS observatories, was launched on July 15, 2004. Aura is designed to make comprehensive stratospheric and tropospheric composition measurements from its four instruments, HIRDLS, MLS, OMI and TES. These four instruments work in synergy to provide data on ozone trends, air quality and climate change. The instruments observe in the nadir and limb and provide the best horizontal and vertical resolution ever achieved from space. After over one year in orbit the instruments are nearly operational and providing data to the scientific community. We summarize the mission, instruments, and initial results and give examples of how Aura will provide continuity to earlier chemistry missions.

Keywords: satellite observations, atmospheric composition

1. Introduction

NASA's Earth Observing System Program began in the late 1980s with the selection of a large number of Earth science instruments and interdisciplinary science teams. The present EOS compliment of satellites consists of three core platforms, Terra, Aqua and AURA and several smaller satellites such as SORCE and ICESAT. Terra, launched in late 1999, focuses on land processes. Aqua, launched in 2002, focuses on the hydrological cycle. Aura, whose focus is atmospheric composition, was launched July 15, 2004 into an ascending node 705 km sun-synchronous polar orbit with a 98° inclination with an equator-crossing time of 13:45. Aura flies in formation about 15 minutes behind Aqua. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and Cloudsat, that were launched together in the Summer of 2006, fly a few minutes behind Aqua. This group of satellites, including the CNES PARASOL satellite, launched in December 2004, and the ESSP Orbiting Carbon Observatory (OCO), scheduled for launch in 2008, are referred to as the "A-Train" The measurements from Aura will be within 30 minutes of these other

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TABLE I
Summary of Aura's four instruments.

Acronym	Name	Instrument PI	Constituent	Instrument description
HIRDLS	High Resolution Dynamics Limb Sounder	John Gille, NCAR & U. of Colorado, Boulder, USA; John Barnett, Oxford University	Profiles of T, O_3, H_2O, CH_4, N_2O, NO_2, HNO_3, N_2O_5, CF_3Cl, CF_2Cl_2, $ClONO_2$, Aerosols	Limb IR filter radiometer from 6.2 μm to 17.76 μm. 1.2 km vertical resolution up to 50 km.
MLS	Microwave Limb Sounder	Joe Waters, JPL, Pasadena, USA	Profiles of T, H_2O, O_3, ClO, BrO, HCl, OH, HO_2, HNO_3, HCN, N_2O, CO, Cloud ice	Microwave limb sounder, 118 GHz–2.5 THz. 1.5–3 km vertical resolution.
OMI	Ozone Monitoring Instrument	Pieternel Levelt, KNMI, The Netherlands	Column O_3, SO_2, aerosols, NO_2, BrO, OClO, HCHO, UVB, cloud top pressure, O_3 profiles	Hyperspectral nadir imager, 114° FOV, 270–500 nm. 13 × 24 km footprint for O_3 and aerosols.
TES	Tropospheric Emission Spectrometer	Reinhard Beer, Mike Gunson, JPL, Pasadena, USA	Profiles of T, O_3, NO_2, CO, HNO_3, CH_4, H_2O	Limb (to 34 km) and nadir Fourier Transform IR spectrometer, 3.2–15.4 μm. Nadir footprint 5.3 × 8.5 km, limb 2.3 km.

platforms. The A-Train can be thought of as a extended instrument package focusing on climate change. Although NASA's TOMS, SBUV, UARS and NOAA's SBUV/2 series of instruments are not formally part of EOS, they have played a key role in NASA's EOS program by collecting a highly accurate and comprehensive long term data set of ozone and atmospheric species active in its chemistry.

The Aura spacecraft carries four chemistry instruments, the High Resolution Dynamics Limb Sounder (HIRDLS), the Microwave Limb Sounder (MLS), the Ozone Monitoring Instrument (OMI) and the Tropospheric Emission Spectrometer (TES), that operate in the wavelength range from the ultraviolet to the millimeter wave region. The instruments and their data are summarized in Table I. These instruments were selected because of (1) their complementary measurements; (2) their technological heritage; and (3) the new capabilities they bring to measuring the

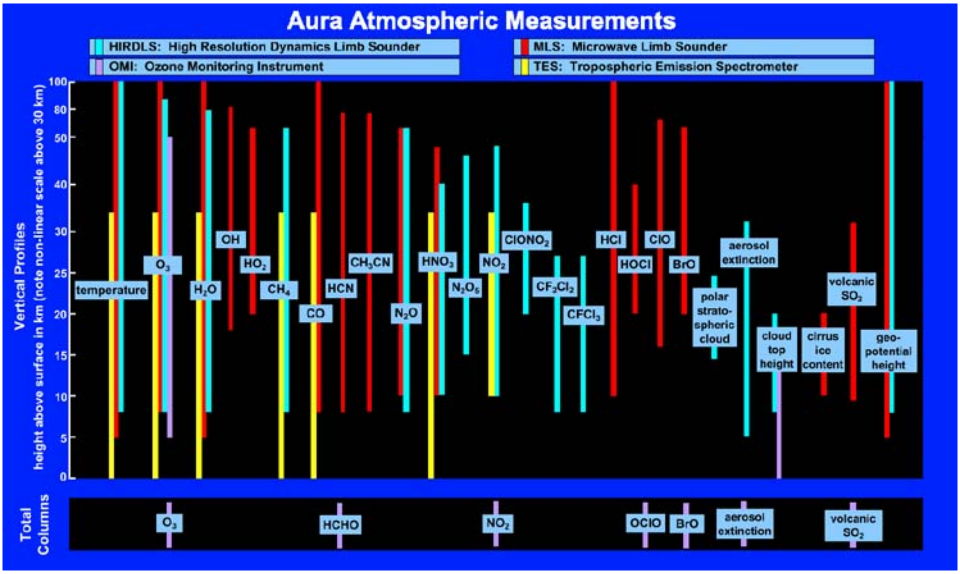

Figure 1. Aura data products and their height range depicted here are based on pre-launch design. For HIRDLS, full capability is not yet demonstrated, but 50 km is the upper limit of the measurements and measures in one azimuth direction only because of a field of view obscuration. TES limb measurements are limited because of mirror drive problems. Column measurements by OMI are indicated in the lower part of the figure (Figure courtesy of J. Waters).

Earth's atmosphere. Below we describe the objectives and science strategy of the Aura mission. Figure 1 graphically shows the vertical range of the Aura instrument data products.

2. Science Objectives of the Aura Mission

The objective of the Aura mission is to attack three principal science questions: Is the ozone layer changing as expected and is there a response to the Montreal Protocol? Where are the sources and what are the processes that control tropospheric pollutants? What are the roles of upper tropospheric aerosols, water vapor, and ozone in climate change? These questions are being answered with the data sets compiled as shown in Table I and illustrated in Figure 1. Most importantly these data are being collected with high vertical and horizontal resolution throughout the atmosphere. Also, when combined with measurements from ground, balloon, aircraft missions, and other measurements from the A-Train, Envisat, ODIN, and ACE, they will provide unprecedented insights into the chemical and dynamical processes associated with our atmosphere. The Aura science questions and the impact the Aura instruments will have on these questions are reviewed below.

2.1. Is the Ozone Layer Changing as Expected?

Total Ozone Mapping Spectrometer (TOMS) observations from 1978 to the present show decreasing trends in ozone both at midlatitudes and in polar regions. Although the Antarctic ozone hole appears to be no longer growing and chlorine levels in the stratosphere are beginning to decline, very significant ozone depletions have occurred in the Arctic (Newman *et al.*, 1997; WMO, 2002). As a result of international agreements, tropospheric chlorofluorocarbons concentrations have begun to decrease. HALOE (UARS) data show a flattening in the stratospheric chlorine reservoir concentrations (Anderson *et al.*, 2000) although an unambiguous decrease has not been detected. A decrease in chlorine should lead to recovery of the ozone layer, but the recovery in the polar regions may be delayed by increases in greenhouse gases which can cool the stratosphere and with possible increases in stratospheric water giving rise to more frequent and persistent polar stratospheric clouds (Solomon, 1999). Stratospheric water vapor does appear to be increasing faster than can be accounted for by the secular trend in methane. As a result of the uncertainty in stratospheric trace gas measurements, current models used to assess the ozone layer do not agree on the timing of the recovery of ozone (WMO, 2002).

Determining the recovery of ozone and the effectiveness of the CFC regulating protocols is a major science objective for HIRDLS, MLS and OMI. The stratospheric measurements made by these instruments will permit a very complete assessment of the chemical processes controlling ozone. All three of the major radicals that destroy ozone (ClO, OH and NO) are being made by HIRDLS and MLS along with the main reservoir gases, HCl, $ClONO_2$ and HNO_3. In addition, the Aura instruments payload make measurements of chlorine and nitrogen sources gases as well as long lived tracers of motion, e.g., N_2O, H_2O, and CH_4. OMI continues the column and profile ozone trends from TOMS/SBUV but with higher horizontal resolution.

2.2. Where Are Sources of and What Are the Processes that Control Tropospheric Pollutants?

Observations have shown that human activities have likely increased surface-level ozone concentrations (Guicherit and Roemer, 2000; Logan, 1985). Decades of research and regulations now reveal that a global approach is required to understand sources and sinks of pollutants such as ozone and its precursors. Tropospheric ozone production occurs when volatile organic compounds (VOCs) and nitrogen oxides (NO_x) are exposed to sunlight in the presence of water vapor. Since the emissions of these ozone precursors are directly linked to today's urban and industrial lifestyle, reductions are both socially and economically costly. For this reason, policy makers have sought guidance from the scientific community in determining effective ways to meet health-based ozone standards or goals. The response of ozone to changes in VOCs and NO_x emissions can be quite complex and variable. Moreover, winds can transport both ozone and its precursors over large distances; and, as a result, exposure to elevated ozone can arise from both local and distant sources. The Aura mission is designed to produce a global assessment of tropospheric ozone, its precursors and controlling gases. The measurements from TES (CO and CH_4) as well as measurements from OMI (NO_2, ozone, and aerosols) combined are providing important data on these processes. Both OMI and TES make complimentary measurements of tropospheric ozone.

2.3. How Do Upper Tropospheric Aerosols, Water Vapor and Ozone Affect Climate Change?

The importance of the upper troposphere/lower stratosphere (UT/LS) in chemistry and climate problems is well stated in a number of international assessment documents (i.e., Houghton *et al.*, 2001). Within the context of chemical problems one of the largest uncertainties is how much ozone and odd nitrogen is supplied to the troposphere from the stratosphere (Hauglustaine *et al.*, 1998). Even estimates of the cross-tropopause flux of ozone from the stratosphere are uncertain to within 15% or greater (Gettelman *et al.*, 1997; WMO, 2002). There are fundamental climate change questions related to moistening or drying of the upper troposphere as convective activity changes. For example, it is now understood that the IR cooling of the atmosphere is strongly influenced by upper tropospheric/lower stratospheric water vapor, aerosols and ozone (Houghton *et al.*, 2001). On decadal time scales, signals from greenhouse gas changes and signals from the changes in reactive constituents are intertwined and difficult to untangle. The tropopause is a complex internal boundary within the atmosphere related to both radiative and dynamical mechanisms. Because the concentrations of many trace gases vary greatly across the tropopause, changes in the UT/LS impact not only the radiative attributes of the atmosphere, but also the chemical environment.

The location and intensity of both tropical and mid-latitude stratosphere-troposphere exchange is key to our ability to quantify the properties of the UT/LS. One of the major science questions Aura measurements addresses is why stratospheric water vapor is increasing. Stratospheric water vapor concentrations are increasing faster than can be accounted for by increases in methane, which is the major in situ source of water vapor in the stratosphere. A number of hypotheses suggest that changes in the freeze-dry mechanism at the tropical tropopause are producing an increase in water transport into the stratosphere. Untangling the complex freeze-dry mechanism of the tropical tropopause is one of the goals of the Aura science team. Relative to the upper troposphere / lower stratosphere dynamics and chemistry, Aura instruments will make key measurements of ozone, water vapor, ice particles and long lived trace gases that will give lead to a better understanding of the dynamics and chemistry of that region. HIRDLS high vertical resolution measurements in the UT/LS are especially important.

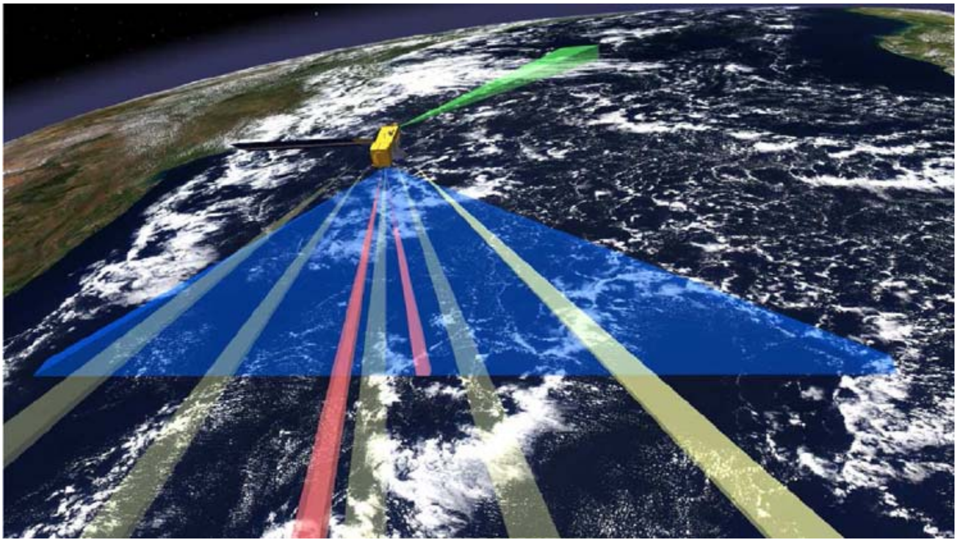

Figure 2. Aura instrument fields of view are shown as colored beams looking from behind the spacecraft. MLS performs forward limb sounding (green). OMI nadir measurement is the blue swath. TES limb and nadir measurements are pink. HIRDLS will only be able to make measurements in the brighter yellow scan position rather than the planned five azimuth positions, because of the blockage.

3. Spacecraft and Instrument Descriptions

The Aura spacecraft orbits at 705 km in a sun-synchronous orbit (98° inclination) with a 13:45 equator crossing time. Aura limb instruments were all designed to observe roughly along the orbit plane; however, with the HIRDLS anomaly discussed below, HIRDLS observations are limited to East (dayside) of the Aura ground track. MLS measures in the forward velocity direction. HIRDLS and TES make limb soundings in the anti-velocity direction. OMI and TES make nadir soundings as shown in Figure 2. The advantage of this instrument configuration is that each of the instruments observes the same air mass within minutes.

3.1. HIRDLS

HIRDLS is a 21-channel infrared limb-scanning filter radiometer designed to make the measurements listed in Table I (Gille *et al.*, 2003). HIRDLS can also determine the altitude of polar stratospheric clouds and detect sub-visible cirrus clouds. The HIRDLS instrument has a long heritage extending back to Nimbus-6 (1975), and was designed to obtain profiles over the entire globe, including the poles, both day and night. Complete Earth coverage (including polar night) could be obtained in 12 hours. HIRDLS was designed to achieve high horizontal resolution using commandable azimuth scans which, in conjunction with a rapid elevation scan, would provide profiles up to 3000 km apart in an across-track swath. The primary advantage of HIRDLS over all other previous infrared limb instruments is its high vertical and horizontal resolution which extends from the upper troposphere throughout the stratosphere.

Current status: After launch engineering studies concluded that a piece of thermal blanketing material ruptured from the back of the instrument during the explosive decompression of launch and covered most of the scan mirror. Even with this blockage, high vertical resolution measurements are still made at one scan angle. As of this writing, the HIRDLS team has demonstrated temperature and ozone retrievals with the instrument and they believe that they can retrieve most of the other constituents as planned. HIRDLS will no longer have its designed horizontal coverage and the partially blocked scan mirror will not allow measurements over the Antarctic.

3.2. MLS

MLS uses microwave emission to measure stratospheric and upper tropospheric temperature and constituents (Table I) (Waters *et al.*, 1999, 2005). MLS also has unique capability to measure upper tropospheric water vapor in the presence of tropical cirrus, and also the cirrus ice content. Aura MLS continues the successful effort of UARS MLS (Waters *et al.*, 1993) using advanced technology to provide new measurements. These measurements are especially valuable for diagnosing the potential for severe loss of Arctic ozone during the critical period when abundances of stratospheric chlorine will still be high and slight cooling of the stratosphere could exacerbate ozone loss due to chlorine chemistry. MLS is making the first global measurements of OH, HO_2 and BrO, constituents that play an important role in stratospheric chemistry.

MLS made comprehensive measurements of the evolution of the Antarctic ozone hole. Figure 3 illustrates MLS observations during the 2004 polar vortex breakup at the 520 K level (20 km). The vortex broke into several fragments between 5 and 11 December, and the evolution and erosion of those fragments is shown through late December, when only one weak fragment remained. After chlorine deactivation by early October, high vortex HCl and very strong HCl gradients across the vortex edge made it an excellent tracer of vortex evolution and morphology.

The MLS instrument aboard UARS has demonstrated the capability of measuring upper tropospheric water vapor profiles (Read *et al.*, 1995; Sandor *et al.*, 1998). Aura MLS measurements are being made the presence of tropical cirrus, where important processes affecting climate variability occur. MLS also provides unique measurements of cirrus ice content. The simultaneous MLS measurements of upper tropospheric water vapor, ice content, and temperature, under all conditions and with good vertical resolution, will make a major contribution to improving our understanding of large scale meteorological systems (such as

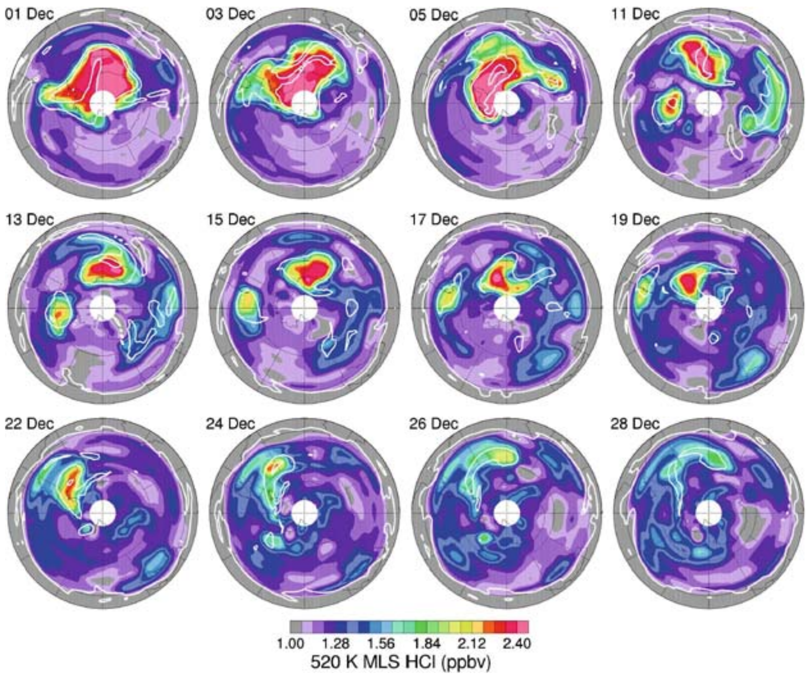

Figure 3. MLS HCl in the lower stratosphere (520 K, 20 km) detailing the springtime breakup of the 2004 Antarctic vortex.

El Niño) affecting the distribution of atmospheric water, climate variability, and tropospheric-stratospheric exchange. The simultaneous measurements of dynamical tracers CO and N_2O enhance the value of this data set by helping identify stratospheric or tropospheric source regions of the observed air masses.

MLS' ability to measure water vapor in the UT/LS is illustrated in Figure 4, which shows the tropical water vapor "tape recorder" (Mote *et al.*, 1996) as seen by MLS. HALOE observed this phenomenon over the lifetime of UARS and illustrated a quasibiennial effect. Continuation of this record will provide important data in understanding the stratospheric water vapor budget. MLS will also continue the HCl record produced by HALOE on UARS (Anderson *et al.*, 2000). There will be at a least one year overlap between Aura and UARS which will insure that possible biases between instruments will be reconciled. HCl is the major reservoir for active chlorine in the stratosphere.

3.3. OMI

The OMI instrument is a contribution of the Netherlands's Agency for Aerospace Programs (NIVR) in collaboration with the Finnish Meteorological Institute (FMI) to the EOS Aura mission. OMI will continue the TOMS record for total ozone

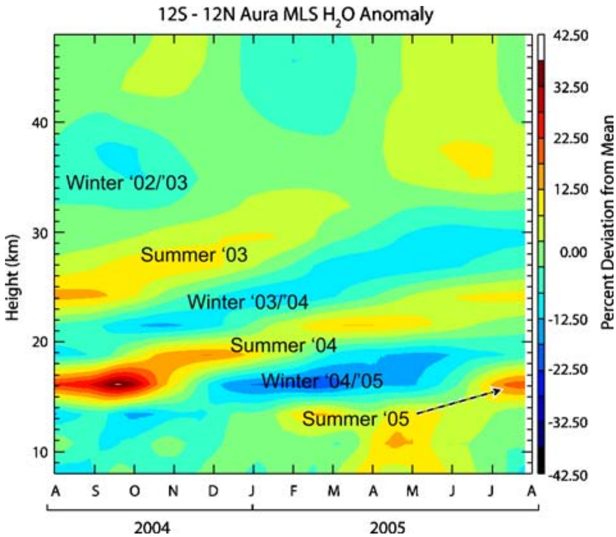

Figure 4. Zonal mean tropical water vapor anomalies recorded by MLS showing the upward propagating dry and wet regions associated with the annual modulation of the tropical tropopause temperature. Date labels show when the bands formed. Average mixing ratios are shown in red.

and other atmospheric parameters related to ozone chemistry and climate (Levelt *et al*., 2005). The OMI instrument employs hyperspectral imaging in a push-broom mode to observe solar backscatter radiation in the visible and ultraviolet. The Earth is viewed in 740 wavelength bands along the satellite track with a swath large enough to provide global coverage in one day (14 orbits) with a nominal 13×24 km spatial resolution in the nadir. The hyperspectral capabilities will improve the accuracy and precision of the total ozone amounts and will also allow for accurate radiometric and wavelength self calibration over the long term. Aside from the measurements listed in Table I, the OMI instrument can distinguish between aerosol types, such as smoke, dust, and sulfates, and can measure cloud pressure and coverage, which provide data to derive tropospheric ozone. A combination of algorithms including TOMS version 8, differential optical Absorption Spectroscopy (DOAS), hyperspectral BUV retrievals and forward modeling will be used together to extract the various OMI data products. NASA will no longer fly TOMS instruments, therefore OMI will continue the long term ozone record produced by TOMS and in particular will provide daily maps of total ozone including the polar regions where the evolution and extend of the Antarctic ozone hole and Arctic depletion are being mapped. The careful calibration techniques developed for TOMS has also been applied to OMI data. The extent of the depletion has been quantified and added to the TOMS long term record, which is illustrated in Figure 5 and reported to the Intergovernmental Panel on Climate Change (IPCC, 2005).

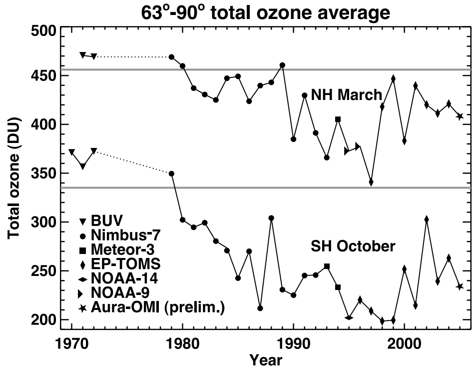

Figure 5. Average column ozone poleward of 63°N latitude in the Spring time of each hemisphere (March for the North and October for the South), in Dobson units, based on various indicated satellites. OMI data is the point (star) at the end of the Northern hemisphere record.

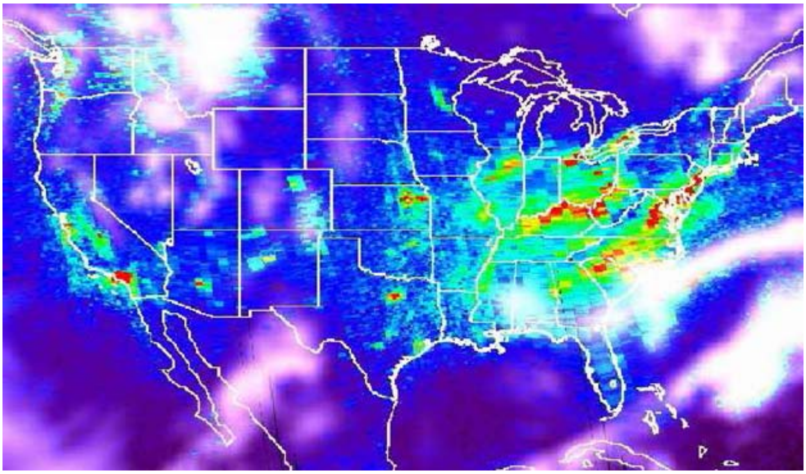

Figure 6. NO_2 measured by OMI over the United States on April 14, 2005. Red is high and blue are low values. White areas are clouds.

Another objective of OMI is to measure tropospheric ozone and one of its precursors, NO_2. OMI measures this constituent with a spatial resolution of 13×24 km at nadir on a daily global basis. This product is under intensive validation, however a sample is shown in Figure 6. OMI's high resolution clearly shows excess amounts over major cities and industrial areas as unique sources.

OMI is producing all of the other data products listed in Table I for which there are similar examples. However the size limitation for this paper prevents describing those products.

3.4. TES

TES is a high-resolution infrared-imaging Fourier transform spectrometer with spectral coverage of 3.2 to 15.4 μm at a spectral resolution of 0.025 cm^{-1}, thus offering line-width-limited discrimination of essentially all radiatively active molecular species in the Earth's lower atmosphere (Glavich and Beer, 1991; Beer *et al.*, 2001). The very high spectral resolution enables the detection of atmospheric composition in the troposphere. TES was built with the capability to make both limb and nadir observations, but the limb observations were curtailed to relieve the mirror drive mechanism. In the limb mode, TES has a height resolution of 2.3 km, with coverage from 0 to 34 km. In the nadir mode, it has a ground spatial resolution of 5.3 $\times$ 8.5 km. TES is also pointable and can access any target within 45° of the local vertical, or produce regional transects up to 885 km length without any gaps in coverage. TES employs both the natural thermal emission of the surface and atmosphere and reflected sunlight, thereby providing day-night coverage anywhere on the globe. In the survey mode, TES will provide global measurements of tropospheric ozone and its photochemical precursors as listed in Table I. Space limitations do not permit illustrating additional TES data products.

TES nadir observations contain about three pieces of information in the troposphere. Figure 7 illustrates CO measurements at 681 hPa. Tropical biomass burning and fossil fuel combustion are clearly seen as sources of CO. Because TES retrieves the entire spectrum from 3.2 to 15.4 μm at high spectral resolution many other gases can be retrieved in a research mode (e.g., ammonia and organics).

3.5. Instrument Synergy

MLS and HIRDLS will provide high vertical resolution profiles which are nearly simultaneous with the OMI observations, and extend down to and below the tropopause. Thus it will be possible to combine observations from these three instruments with meteorological data to produce effective separation of the stratospheric component of the total column ozone and thus provide an estimate of the tropospheric ozone column (sometimes called the total ozone residual). The residual can be compared to TES tropospheric profiles of O_3. The combination of instruments will make it possible to understand the stratospheric and tropopause contributions to O_3 as well as the transport, physical and chemical processes which affect their distributions.

HIRDLS and MLS make complimentary measurements in the stratosphere, which afford better interpretation of photochemical processes involving constituents measured nearly simultaneously. For example, HNO_3, OH, NO_2 and N_2O_5 are related through their principal production and loss processes throughout the stratosphere. MLS will measure OH and HNO_3. HIRDLS will measure HNO_3, NO_2 and N_2O_5. A second example involves chlorine species. Related gases are

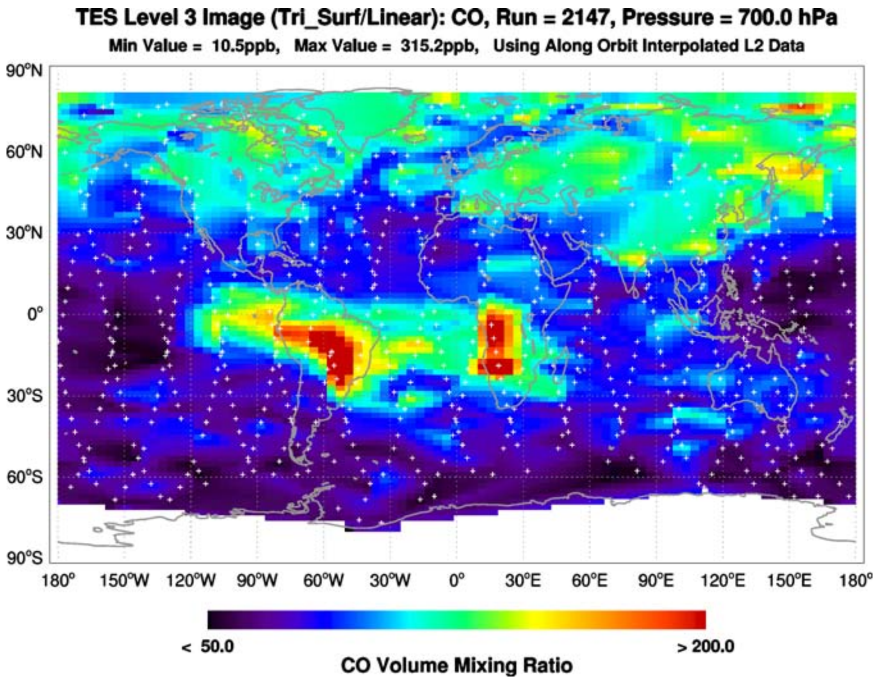

Figure 7. TES CO at 681 hPa pressure levels from their global survey mode. Measurements are made at the white crosses and interpolated to form a map. Northern hemispheric fossil fuel combustion sources and tropical biomass burning are evident sources of CO.

HCl, $ClONO_2$, ClO, NO_2, and O_3 (which controls the relative concentrations of HCl and $ClONO_2$). Here, $ClONO_2$, NO_2 and O_3 are measured by HIRDLS, and HCl, ClO, and O_3 are measured by MLS. Combining such observations to make important tests of chemical processes on the global scale has been successfully demonstrated using CLAES, MLS, and HALOE on UARS.

3.6. Synergy with the A-Train and International Missions

The Aura spacecraft flies 15 minutes behind the Aqua spacecraft which means that many of the measurements on Aura will be made shortly after Aqua. About one minute behind the Aqua spacecraft, CloudSat and CALIPSO will make measurements of cloud properties using active radar and lidars, respectively. Because MLS is a limb sounder and is observing on the front of the Aura spacecraft, MLS measurements are effectively only about 7 minutes behind those being made by the Aqua nadir sounders. The MLS measurements of upper tropospheric water vapor and temperature in the limb (Read *et al.*, 1995) will be complementary to those made by AIRS and AMSU aboard Aqua. Synergies are also expected with Envisat, ACE and OSIRIS since common and complementary measurements are being made in the stratosphere and in some cases the troposphere. A unique opportunity exists to discriminate diurnal variations since the crossing times of these satellites differ for a given location. Very careful calibration and validation are needed to make these discriminations.

4. Summary

The EOS Aura mission was successfully launched on July 15, 2004. With the exception of HIRDLS, all of the instruments are functioning as designed, although to preserve instrument life, TES is now operating only in the nadir mode. Aura is providing the next level of measurements needed by the stratospheric and tropospheric community to advance the science and to answer the crucial broad questions: Is the stratospheric ozone layer recovering? How is the chemistry of the troposphere changing? What are the roles of upper tropospheric aerosols, water vapor and ozone in climate change? The four instruments on Aura provide the needed sets of measurements to answer these broad questions. Further synergies are expected with the A-Train and other international missions. The Aura measurements will continue important atmospheric composition measurements started with earlier satellites such as TOMS and UARS. Good overlap will occur thus providing valuable data on ozone and climate assessments.

For more information on the Aura platform and instruments, please refer to the web site `http://aura.gsfc.nasa.gov`. A pre-launch version of this paper was published in EOS (Schoeberl *et al.*, 2004). A special issue of the IEEE journal of *Transactions on Geoscience and Remote Sensing* will appear in 2006 which will highlight Aura, its instruments, retrieval algorithms, and data examples. Many results will soon be appearing in the atmospheric science literature.

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